WMAP 3-year polarization data: Implications for the reionization history

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With the three-year data, the *Wilkinson Microwave Anisotropy Probe* (WMAP3) produced a more accurate determination of the electron scattering optical depth, downwarding its value from $\tau_{es} = 0.17 \pm 0.08$ obtained with the first-year data (WMAP1) to $\tau_{es} = 0.09 \pm 0.03$. As a consequence, the structure formation in the ΛCDM best fit model obtained WMAP3 is delayed relative to that of WMAP1.

We show that the delay of structure formation can not fully account for the reduction of τ_{es} from WMAP1 to WMAP3 when the radiative transfer effects and feedback mechanisms are took into account in computing the reionization history of the Universe.

We also show that a PopIII stellar cluster with a mass of $80 M_\odot$ and a heavy Larson initial mass function has an ionizing efficiency high enough to account for WMAP3 results, while in the case of WMAP1, a higher stellar mass of $1000 M_\odot$ was required.

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1. Introduction

With the three-year data on the anisotropy of the cosmic microwave background (CMB) and its polarization, the *Wilkinson Microwave Anisotropy Probe* (WMAP3) produced a more accurate determination of the electron scattering optical depth, downwarding its value from $\tau_{es} = 0.17 \pm 0.08$ [1] obtained with the first-year data (WMAP1) to $\tau_{es} = 0.09 \pm 0.03$ [2, 3], consistent with an abrupt reionization at redshift $z_{re} \simeq 11$, significantly later than $z_{re} \simeq 17$ as implied by WMPA1.

Common to most attemps to explain the high value of τ_{es} obtained by WMAP1 was the assumption that the globally-average ionization fraction decreases over a limited period of cosmic time (the so called "double reionization"), stimulating speculations regarding the efficiency of star formation and the escape fraction of the ionizing photons into the intergalactic medium (IGM). Some studies [4, 5] agree on the necessity of the existence of a first generation of metal-free stars (PopIII stars) with heavy initial mass function (IMF). Other works [6, 7] found that the metal enriched stars (PopII stars) are able to reionize the Universe sufficiently early to produce the high values of τ_{es}. Other proposed physical mechanisms are radiative, the most important being photoionization heating and photodissociation cooling of the molecular hydrogen. A recent work [8] critically examined the plausibility of different mechanisms showing that the double reionization requires a rapid drop in ionizing emissivity over a single recombination time that can be obtained with unusual choices of the physical parameters.

Other most important changes of the cosmological parameters from WMAP1 to WMAP3 are the reduction of the normalization of the power spectrum on large scales ($\sigma_8 = 0.92 \to 0.76$) and the reduction of the scalar spectral index of the primordial density perturbations ($n_s = 0.98 \to 0.74$). As a consequence, the structure formation in the ΛCDM model with the primordial power spectrum of the density fluctuation obtained by WMAP3 is delayed relative to that of WMAP1.
Based on the simple assumption of constant ionizing efficiency, a recent paper [9] claims that the delay of structure formation controls the reionization in WMAP3 best fit model such that, if ionizing efficiency is large enough to make reionization early and $\tau_{es} = 0.17$ in WMAP1 case, the same efficiency is required to have the reionization later and $\tau_{es} = 0.09$ in WMAP3 case.

In this paper we show that the delay of structure formation can not fully account for the reduction of τ_{es} value from WMAP1 to WMAP3 best fit models when the radiative transfer effects and feedback mechanisms are take into account in computing the reionization history of the Universe. We also show that a PopIII stellar cluster with a mass of $\sim 80 M_\odot$ and a heavy Larson IMF has an ionizing efficiency high enough to account for the value of τ_{es} obtained by WMAP3.
Throughout we assume a background cosmology consistent with the most recent cosmological measurements [3] with energy density of $\Omega_m = 0.24$ in matter, $\Omega_b = 0.044$ in baryons, $\Omega_\Lambda = 0.76$ in cosmological constant, a Hubble constant of H_0=72 km s^{-1}Mpc^{-1} and adiabatic initial conditions of the density fluctuations.

2. WMAP 3-year data: implications for the properties of ionizing sources

The mean ultraviolet radiation background (UVB) intensity responsable for the cosmological reionization, $J(\nu_0, z_0)$, observed at the frequency ν_0 and the redshift z_0 produced by a population

Model	n_s	σ_8	$M/M_\odot$	τ_{es}
WMAP1	0.99±0.04	0.92±0.1	1000	0.157±0.032
WMAP3	0.961±0.017	0.76±0.05	80	0.093±0.012
WMAP*	0.99±0.04	0.92±0.1	80	0.130±0.032

Table 1: Model parameters
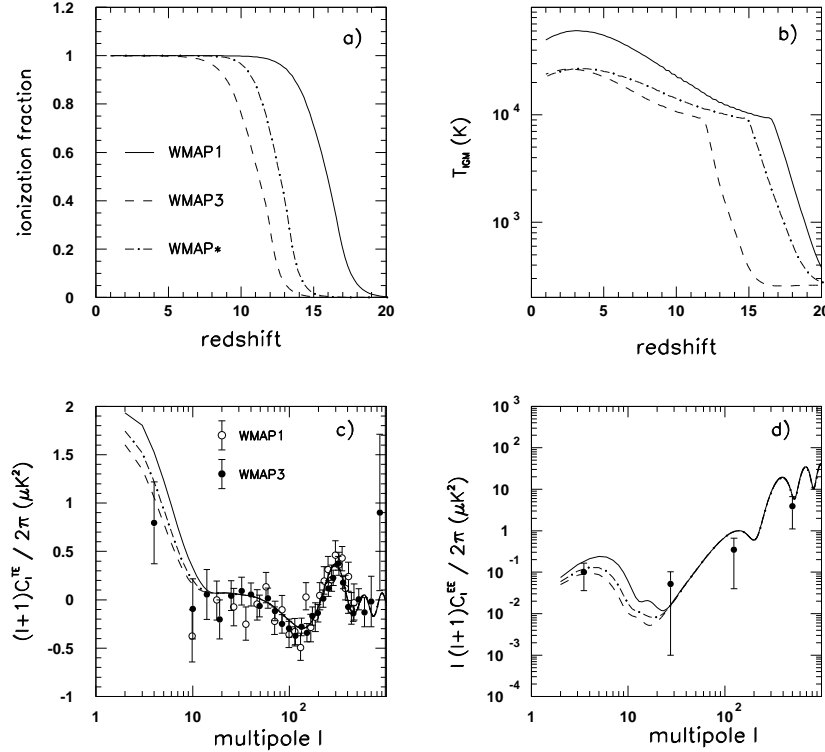
Figure 1: Panel a): Reionization histories obtained for the models given in Table 1. Panel b): Redshift evolution of the IGM temperature corresponding to the reionization histories presented. Panel c): TE angular power spectra for different reionization histories compared with WMAP1 and WMAP3 experimental measurements. Panel d): EE angular power spectra for different reionization histories compared with WMAP3 experimental measurements.

of sources characterized by the comoving emmisivity $\varepsilon_\nu(z)$ can be written as:

$$J(\nu_0, z_0) = \frac{c}{4\pi} \int_{z_0}^{\infty} \varepsilon_\nu(z) e^{-\tau_{eff}(\nu_0, z_0, z)} \frac{dt}{dz} dz,$$

$$\varepsilon_\nu(z) = \bar{L}(z) \bar{\tau}_{lf} f_* \frac{\omega_b}{\omega_m} \frac{d}{dt} \int_{M_{min}(z)}^{\infty} \frac{dn}{dM_h}(M_h, z) M_h dM_h. \qquad (2.1)$$

In the above equation $\nu = \nu_0(1+z)/(1+z_0)$, $(dt/dz)^{-1} = -H_0(1+z)\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$ is the line element in our ΛCDM cosmological model, τ_{eff} is the IGM effective otical depth, $n(M_h, z)$ is

the comoving number density of halos of mass M_h at redshift z given by Press-Shechter formalism, $\bar{L}(z)$ is the mean specific luminosity of the ionizing sources, $\bar{\tau}_{lf}$ is their mean lifetime and f_* is the star formation efficiency.

We compute the mean specific luminosity $\bar{L}(z)$ for the emission of a PopIII stellar cluster according to [10]:

$$\bar{L}(z) = \int_{M_l}^{M_u} F(v,M,z)\Phi(M)dM, \quad F(v,M,z) = l_v^{st}(M) + l_v^{neb}(M) + l_v^{Ly\alpha}(M,z), \tag{2.2}$$

where: $\Phi(M)$ is the heavy Larson IMF, $\Phi(M) \sim M^{-1}(M/M_c)^{-1.35}$ with $M_c = 15M_\odot$ normalized so that: $\int_{M_l}^{M_u} \Phi(M)dM = 1$, $l_v^{st}(M)$ is the spectrum of the star with the mass M, $l_v^{neb}(M)$ is the emission from its nebulae, $l_v^{Ly\alpha}(M,z)$ is the emission from $Ly\alpha$ photons and M_L and M_u are the lower and upper mass limits of the IMF.

We adopt the spectra of PopIII stars from [11] with $M_l = 80M_\odot$ and $M_u = 1000M_\odot$ and compute the redshift evolution of the reionization fraction for different values of parameters (n_s, σ_8, M) and the coresponding τ_{es} by using the equations (1.1) and (1.2).

Our computation includes all the radiative mechanisms relevant for the primordial gas dynamics: photo-ionization, photo-heating and cooling of the hydrogen and helium in the expanding Universe. The mean UVB flux is obtained as solution to the radiative transfer equation by assuming a constant star formation efficiency $f_* = 0.1$.

The model parameters and the corresponding values of τ_{es} are given in Table 1. The model WMAP* was constructed to have the same values for n_s and σ_8 as WMAP1 and the same stellar mass as WMAP3.

We find that a stellar cluster with a mass of $M \simeq 80M_\odot$ has an ionizing efficiency high enough to account for WMAP3 value of τ_{es} while for the case of WMAP1 a higher stellar mass, $M \simeq 1000M_\odot$, is needed. For WMAP* model we obtain a value of the electron optical depth of $\simeq 0.13$ that can account for about 80% from that obtained by WMAP1.

Panel a) from Figure 1 presents the redshift evolution of the reionization fraction obtained for the models given in Table 1. In Panel b) we show the redshift evolution of the IGM temperature corresponding to the reionization histories presented and in Panels c) and d) the corresponding TE and EE polarization angular power spectra compared with WMAP experimental measurements.

3. Conclusion

On the basis of these calculations, we conclude that the delay of structure formation in WMAP3 best fit model can not fully account for the reduction of τ_{es} from WMAP1 to WMAP3 when the radiative effects and feedback mechanisms are take into account.

We find also that a PopIII stellar cluster with a mass of $80M_\odot$ and a heavy Larson IMF can account for the WMAP3 results while, in the case of WMAP1, a higher stellar mass of $1000M_\odot$ is required.

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